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Modelling approaches for consequential life-cycle assessment (C-LCA) of bioenergy: Critical review and proposed framework for biogas production

Antonino Marvuglia *, Enrico Benetto, Sameer Rege, Colin Jury

Public Research Centre Henri Tudor (CRPHT)/Resource Centre for Environmental Technologies (CRTE), 6A, avenue des Hauts-Fourneaux, L-4362 Esch-sur-Alzette

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ABSTRACT

Conventional life-cycle inventories (LCIs) are static models not considering any mechanism of revenue maximisation and price equilibrium under external constraints. An additional demand of a given commodity, irrespective of the amount, can always be supplied by the average supplier under fully elastic market assumption. This constitutes a recognised limitation for the application of LCA to the assessment of the environmental consequences of changes applied to complex systems, like agro-systems. In the so-called consequential LCI (C-LCI), the relationships between the activities and processes of a life-cycle are no longer seen as essentially technical connections, based on average data; instead the determining socio-economic mechanisms are considered via market information and eventually economic models (partial or computable general equilibrium). The practical implementation of C-LCI is however still obscure to many practitioners and the complementarities and overlaps between the different C-LCI modelling approaches have not been completely clarified so far.

This paper aims at filling this gap. The first part of the paper provides a survey of a number of applications using different equilibrium models. Afterwards we critically review the main variables and parameters supporting the definition and implementation of the C-LCI modelling approaches. In the last part of the paper we propose a methodology to integrate economic modelling and LCA in order to perform a C-LCA of biogas production, specifically addressing the indirect land use change (ILUC) issue. Finally we describe the application of this methodology to a case study dealing with the production of biogas in Luxembourg.

Contents

Abbreviations: A-LCA, attributional LCA; CAP, common agricultural policy; CAPRI, common agricultural policy regional impact analysis; CES, constant elasticity of substitution; CGE, computable general equilibrium; C-LCA, consequential LCA; C-LCI, consequential LCI; CRS, constant returns to scale; E, exports; EU, European Union; GAMS, general algebraic modelling system; GHG, greenhouse gas; GTAP, global trade analysis project; ILUC, indirect land use change; IMAGE, integrated model to assess the global environment; KL, capital and labour; KLE, capital, labour and energy; LANCA, land use indicator calculation tool; LCA, life-cycle assessment; LCI, life-cycle inventory; LCIA, life-cycle impact assessment; LES, linear expenditure system; LUC, land use change; M, imports; PEM, partial equilibrium model; SAM, social accounting matrix; SETAC, Society of Environmental Toxicology and Chemistry; XDD, domestic consumption of domestic products.

* Corresponding author. Tel.: +352 4259914652.
E-mail address: antonino.marvuglia@tudor.lu (A. Marvuglia).

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1. Introduction and state of the art

Spurred by the ambitious targets set by the EU to increase the share of renewable energy sources [1], all the member states are currently setting policies at various levels to accelerate the implementation of bioenergy production. However, the increased production of bioenergy from energy crops inevitably induces changes in the land use patterns which, in turn, can lead to substantial impacts, particularly on biodiversity and soil quality [2] and affect other economic activities. The flourishing literature in the field of LCA of crop-based biofuels [3–5], including biowaste [6] and agricultural residuals [7], energy feedstock [8–11] and algae [12,13], shows scattered results and proves that the debate is still far from being concluded.

Several reviews have been conducted so far, which generated a variety of different explanations for the different outcomes of LCA studies [14]. van der Voet et al. [15] reviewed 67 LCA case studies on biofuels, including ethanol and biodiesel from biomass. An important source of divergence among the results has been identified in the assessment of direct and indirect land use change (respectively LUC and ILUC) impacts, which can be accompanied by sometimes large changes in GHG emissions from soils [16]. Searchinger et al. [17] show that including GHG emissions from LUC and ILUC may change a net GHG benefit into a net cost. Another common denominator among the current LCA studies is the poor consideration of side effects, rebound effects, market mechanisms and similar factors due to the difficulty of developing a methodology and finding proper data. In reality, due to the globalisation of markets, the environmental impacts of bioenergy production are seldom confined to a local use of the resources, but they trickle down in a chain of indirect effects that most likely take place outside the biofuels value chain as well.

It is indeed the goal of the so-called consequential LCA to comprehensively assess the consequences, in terms of induced environmental impacts, of human driven actions, most often related to policy or strategic decisions. C-LCA attempts to describe how environmentally relevant flows will change in response to possible decisions [18] and to quantify the relative impacts. It adopts therefore a completely different perspective than conventional (called “attributional”) LCA, which aims at estimating the portion of the global environmental impacts (i.e. the total impacts generated by human economy) which has to be ascribed to a specific technological system. Different approaches have been proposed to quantify the indirect effects to be included in C-LCA. For instance Kløverpris and Wenzel [19], Kløverpris et al. [20,21] and Kløverpris [22] use a dynamic economic model based on GTAP[1] to determine the possible consequences of biofuel production on the agricultural sector, in terms of land use change and affected economic activities. Earles et al. [23] use a multi-market, multi-region partial equilibrium model (PEM)[2] integrated with a life-cycle-based impact assessment to conduct a C-LCA aiming at the estimation of the broad environmental impacts of a change in forest-based policy. Another approach developed by Schmidt [24] is to cut off short- and mid-term changes and focus on the long-term marginal supplier of a specific crop, which e.g. in the EU is barley or wheat according to Weidema [25]. Despite the intrinsic interest of these studies, a structured understanding of the role of the different modelling perspectives in the consequential approach and of the related limitations is still missing [26]. This seems to be a common feature of the most of the C-LCA studies, even outside the bioenergy field [27].

Based on the current state of the art, the aim of this paper is to carry out a structured analysis of the possible modelling approaches for C-LCA, both from the perspective of consequential LCI and of ILUC and LUC impact assessment, while proposing an operational approach for C-LCA of bioenergy, developed for the specific case of biogas production in Luxembourg. In particular, a critical review of three possible modelling approaches for C-LCI (simplified, partial equilibrium, computable general equilibrium models) is provided, with specific focus on the bioenergy sector. In doing so, the paper is meant to provide guidance to researchers on the various modelling questions that have to be taken into account when undertaking the difficult task of carrying out a C-LCA with any of the described three modelling perspectives and to unveil opportunities for their fruitful combination.

1.1. Modelling approaches for consequential LCI

Remaining in the field of biofuels applications, A-LCA estimates the environmental impacts generated by a biofuel technology (for a given functional unit) by describing its life-cycle in terms of inventory of mass and energy flows exchanged by the technical processes involved in biofuel production and use, as well as the assessment of related environmental impacts. Attributional LCIs do not consider any mechanism of revenue maximisation and price equilibrium under external constraints. They are based on the underlying assumption that the processes involved in the life-cycle are operated under steady-state conditions and average data can be used for the LCA because the studied life-cycle does not affect the existing market and surrounding product systems[3] (ceteris paribus assumption). This assumption implies that the amount of the product under assessment is not essential to the study, which is generally accomplished for a conventional amount of the product (functional unit). The results of the study can be simply scaled up or down by any scaling factor, as it is assumed there will always be an average consumer able to absorb the amount of the product at stake introduced into the market and there will always be an average supplier able to meet the demand coming from the market (*fully elastic market*). This condition mostly corresponds to the archetypal situation defined as

[1] https://www.gtap.agecon.purdue.edu/
[2] Called partial market equilibrium (PME) in their paper.
[3] That is, everything else other than those variables that are explicitly allowed or supposed to change remain the same.

"Situation C" in the ILCD handbook [28]. The A-LCA approach is however debatable to support decision making processing dealing with complex systems, like agro-systems, and strategic (or policy) related questions because of the intrinsic limitations of the ceteris paribus assumption which neglects possible significant indirect effects.

In order to tackle such situations, C-LCA can be used to estimate the environmental impacts engendered by the implementation of a biofuel production and use policy at a given scale, considering the actual volume of biofuel involved. The results therefore depend on the actual magnitude of the implementation and are not linearly dependent on the functional unit. C-LCI identifies and characterises (in terms of additional or avoided environmental impacts) all the changes induced on all the affected processes, including the ones which are indirectly related to the biofuel system through market relationships. In C-LCI marginal data[4], instead of average data, are thus commonly used and the relationships between the activities. Processes of a life-cycle are no longer seen as essentially technical connections. Instead, the determining socio-economic mechanisms are considered, eventually via market information and/or economic models, the latter being specifically used to assess non-marginal (large-scale) changes. As highlighted in Finnveden et al. [29], and explained in Börjeson et al. [30], typical situations a C-LCA study of bioenergy production would normally address are:

1. *Normative scenario*: C-LCI of bioenergy production, addressing the following question: what are the environmental consequences associated to *a specific target* in terms of bioenergy production, which is assumed *to happen*?
2. *Predictive scenario*: Launch of an innovative technology for second generation biofuels, where the question to answer is: *what will happen* if this technology will penetrate the market on a large scale?
3. *Explorative scenario*: Large-scale promotion of electricity generated from biomass, where the question to answer is: *what can happen* either from an industrial point of view (if a specific manufacturer decides to invest in an innovative technology) or from a policy-maker point of view (if a country decides to economically support the introduction of this new technology) or from both perspectives if a specific future development unfolds (i.e. if more and more biomass plants worldwide start adopting this technology).

Behind C-LCA there is therefore a decision context oriented to the assessment of the *changes* engendered by possible future actions (whatever their magnitude), whereas A-LCA is purely descriptive (at past, present and future time horizons) and does not provide, in principle, any support to decision making processes.

In order to model the C-LCIs three distinct approaches have been found in the literature: (1) *simplified approach*, based on sort of rules of thumb, which has been primarily developed within the LCA community; *economic modelling approaches*, issued and eventually adapted from other fields of investigation, namely (2) *PEMs* and (3) *CGE models*. In this paper, these approaches are first introduced with respect to the guiding principles and specificities of C-LCI (Sections 1.2–1.4) and then structured against a number of criteria which cover most of the important operational aspects of the C-LCA perspective (Section 2): the setting up of the market boundaries; the definition of the scale of the studied change; the relevance of the time horizon; the consideration of constraints, whatever their type (technical, market, legal, behavioural, etc.); the consideration of multi-output processes; the inclusion of LUC and ILUC and finally the way of quantifying the change to be studied, which is the final goal of any C-LCA study. The final aim of the analysis is to understand how and to what extent the different approaches serve the objectives of C-LCI and eventually how they could be improved.

1.2. Simplified approach

A simplified methodology for C-LCA has been developed in [25,31] and further applied to the agricultural sector in [24]. The methodology considers a set of default assumptions and decision nodes based on given criteria (e.g. long-term or short-term perspective, constrained or unconstrained market, etc.) and could be seen as a collection of "special cases" of dynamic economic modelling. For example, it is assumed that supply equals demand (which is the case for perfect markets in the long term) and the relationship between changes in demand (ΔD) and changes in supply (ΔS) is given by

$$\Delta S = \Delta D \times \frac{\mu_S}{\mu_D} \tag{1}$$

where μ_S and μ_D denote price elasticities on supply and demand, respectively. To the aim of the critical review and comparison of C-LCA modelling approaches, the different nodes and decision criteria which constitute the simplified methodology have been structured in a MindMap tree, provided in the Supporting Information (SI).

The approach relies on market information. For the agricultural sector, elasticity values for the most important crops in most regions of the world can be found in FAPRI.[5] The mechanism of the relationships between crop consumption and LUC is effectively described in Kløverpris et al. [20,21]. Along this type of approach, other authors (e.g. Msangi et al. [32]) propose to derive simple relationships (charts) between variables and parameters of interest that could feed simplified models like the one by Weidema et al. [31].

For the specific case of bioenergy, the mechanisms that have been identified as the common response to an increased demand for a specific crop are *expansion*, *displacement* and *intensification* [22,33]. Expansion of croplands is represented by the transformation of a specific land type into arable land. In order to assess the effects of expansion, the marginal land, i.e. the land to be transformed first, has to be identified. Displacement of other crops substitutes one crop for another and is primarily assumed to occur in countries facing physical and regulatory constraints. Hence, not the marginal land but the marginal crop must be identified. Intensification of existing production increases the yield of a given cultivated area; hence, no additional land area is transformed. However, in order to increase the yield per hectare, additional inputs of water, energy and nutrients are needed, which again increase the environmental burdens on a given area. As long as crops are displaced, the effect of the displacement propagates to the whole global agricultural system until it levels off from intensification and expansion.

A similar approach, only focussed on modelling ILUC impacts, is followed in [34]. Similarly to Weidema et al. [31], but having ILUC as the main driver, the study is based on a causal-descriptive methodology which explores cause and effect relationships to describe the main market responses following an additional demand for a specific crop and derive the consequent ILUC impacts, making wide use of stakeholders' input. It provides an alternative modelling approach to

[4] Under the assumption of perfect competition, supply is determined by marginal cost, i.e. the cost a company incurs into to produce the last unit. Firms will produce additional output as long as the cost of producing an extra unit of output is less than the price they will receive. With marginal data we mean here the inventory data which are determined as a result of the market competition.

[5] http://www.fapri.iastate.edu/

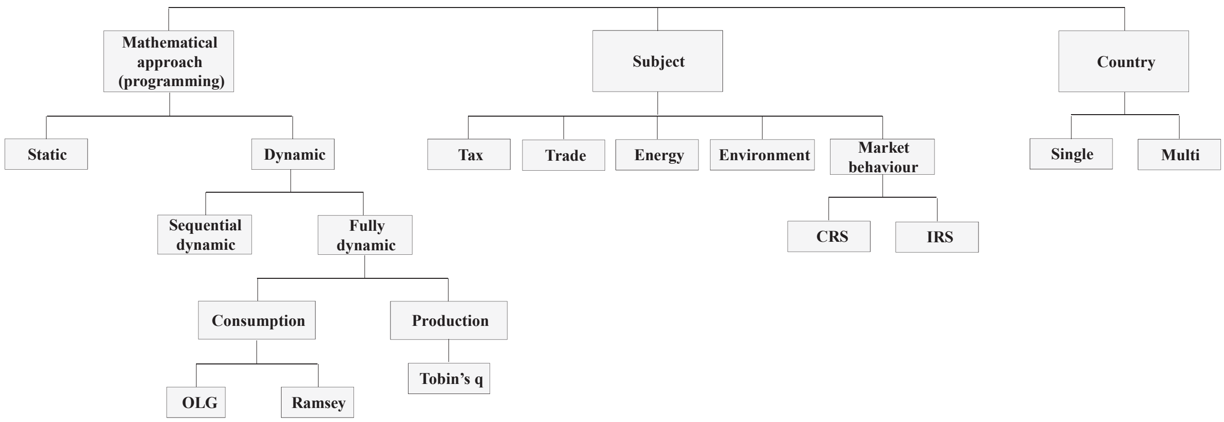

Fig. 1. Generic classification of computable general equilibrium (CGE) models.

the equilibrium models and could potentially be used to inform those models.

1.3. Partial equilibrium models

PEMs confine themselves to only one sector, which in the case of biofuels production is the agriculture sector, and do not account for the impact of prices of other commodities on the consumption and investment decisions (either static or dynamic) of farmers. PEMs can be linear or non-linear at the farm, regional or national level; they can also incorporate the time line of operations like ploughing, disking, planting, harvesting, etc., with constraints on various resources like labour and machinery necessary for each operation. Typically at the farm level, PEMs are primarily oriented to *profit maximisation* of the farm activities and represent a tool for decision making. Farm models at the regional or national level are largely used from a policy perspective to analyse the impacts of policy decisions on the agriculture sector. PEMs would typically have a production function (i.e. the function that specifies the output of the production process for all combinations of inputs) for each crop that would be similar for all crops but varies in the statistically estimated parameters and thus would lead to different outputs based on changes or shocks in inputs like rainfall, irrigation, fertilizer application, soil suitability to crop and temperature. The decision variables available to the farmer would be a function of the exogenous specification of the input prices like fertilizer, cost of irrigation, input subsidies by crop or land type or output subsidies or price support systems and quotas. The farmers would base their decision on the expected future price of the crop, given the past movement of prices. As a result, the changes (e.g. of crop production patterns, including the displaced crops and other agricultural commodities) to be included in the C-LCI can be derived from the PEM, including all the endogenous and exogenous variables and mechanisms, instead of using a simplified approach which is based on special cases.

In the absence of data to estimate production function for crops, the *opportunity cost*[6] approach can be used, wherein the farmer decides to change cropping patterns based on the opportunity cost of the crops. The question is: how much would a farmer gain if one unit of land (acre or hectare) under a particular crop was allocated to the other crops given the cost of inputs, expected output price and subsidies on all crops? The output changes in tons or area (hectares) are computed based on shock to the system in terms of additional demand, or input prices or changes in subsidies, etc. However, there is no iterative process with other markets that determine the prices of crops within the economic system and thus determine the consumption and investment decisions of the farmers.

Among the best known PEMs, AGLINK/COSIMO [35], FAPRI [36] and IMPACT [32] can be mentioned. All these models are global models with a focus on agricultural markets. In the literature on C-LCA, some authors [33,37,38] have applied the approach followed by Schmidt and Weidema [39]. Others [40–44] have applied enhanced versions of the quantitative, market-based, methodology presented by Ekvall [45]. However, none of the abovementioned studies directly applies a full-fledged PEM. An extensive survey of modelling bioenergy in PEMs (not for C-LCA purposes) is provided by Pérez Domínguez and Müller [46].

1.4. Computable general equilibrium models

CGE models incorporate the modelling of economic outcomes in all markets of an economy (as opposed to PEMs which are limited to a specific market) and allow a sufficiently accurate estimate of the price changes when all changes in prices of inputs are accounted for in the system. They come in varieties of flavours depending on the nature of policy issues to be addressed, ranging from static one-country models to dynamic multi-country models. Fig. 1 highlights a possible classification of CGE models based on mathematical formulation of the problem, economic issues addressed and number of countries/regions involved in the analysis. An introduction on these models and working codes in GAMS[7] and R[8] is presented by Fortuna and Rege [47].

Typically CGE models are built on a base year where the modeller can find consistent data for production, consumption and trade. The core assumption is that the economy is assumed to be in equilibrium in the base year and all accounts are consistent. In other words, supply in all markets equals the demand in the corresponding markets. Most models are “sequentially dynamic”, wherein capital at time $t+1$ equals the non-depreciated capital from time t in time $t+1$ and the investment in time t. Thus capital is not a control variable to achieve the maximum of the present discounted value of the money metric utility function over the time horizon of the model.

A typical production function for a sector in a CGE model to analyse energy issues would be as shown in Fig. 2. We consider a general case where there are 20 commodities produced by 16 sectors, each of which produces multiple commodities. The production takes place based on a nested decision making process

[6] Opportunity cost is the cost of any activity measured in terms of the value of the next best alternative forgone (that is not chosen). In the case of the farmer, it is the economic sacrifice related to the second best (i.e. second most remunerative) choice available in terms of crop to plant.

[7] http://www.gams.com/

[8] http://www.r-project.org/

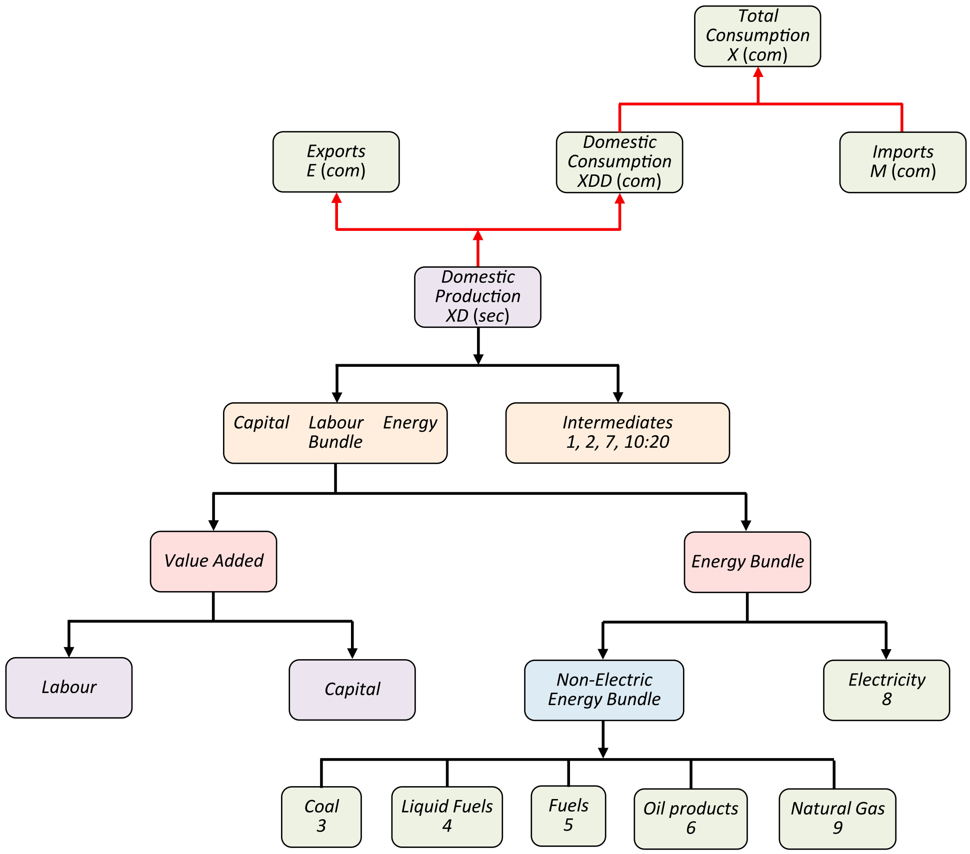

Fig. 2. Typical production function for a sector in a CGE model to analyse energy issues (com, commodity; sec, sector).

with the first nest choosing between the intermediate inputs (commodities 1, 2, 7 and 10:20) and the capital–labour–energy (commodities 3–6, 8, 9) bundle. At the second nest the KLE bundle is split into the value added (KL) and energy. At the third nest the value added is split into capital and labour while the energy is split into different energy commodities like electricity and non-electric energy bundle which further in the nests below gets split into individual energy commodities. The decision to use the commodities depends on the price elasticity (defined as the percentage change in demand to the percentage change in price) of substitution at each nest and any changes here would lead to changes in demand. Elasticities influence the behavioural response to prices and therefore play a role in the calculation of the changes to be included in C-LCI. On the supply side, each sector supplies to the export (E) and domestic markets. Consumption comprises imports (M) and domestic consumption (XDD). The import and domestic consumption are combined using an Armington function to account for the presence of different but homogenous domestic and imported commodities. Each nest has a similar minimisation problem of minimising costs subject to output. The response to trade depends on the values of these elasticities and so are the changes to be included in C-LCI.

According to the time frame of the investigation and depending on assumptions made about the flexibility of production factors, equilibrium models can be classified as *short term*, *medium term* or *long term*. Short term means that some production factors are fixed, and are not allowed to reallocate between alternative uses. The fixed factors will typically be capital, agricultural land, and perhaps agricultural labour. Medium term models allow for reallocation of all production factors as response to some exogenous events. Finally, long-term models also model endogenous capital formation.

An example of application of CGE model to LCA is given in [48,49], where GTAP has been used to predict global economic perturbation that would be caused by two different European energy policies (bioenergy policy and business as usual policy) and the corresponding environmental impacts. One of the main steps of the whole procedure is represented by the mapping of the GTAP database to the ecoinvent® LCI database at the aim of establishing the emissions and extractions from ecosystems caused by each economic sector. However, this is not a straightforward operation, since there is not an exact correspondence between the two databases: more than one economic sector is often involved in one ecoinvent® process. Therefore, the authors segmented the ecoinvent® database according to the GTAP economic sectors in order to avoid double counting of indirect environmental impacts. Important limitations of this approach are: (i) the lack of accuracy of land use modelling, which is a major issue when dealing with biofuels; (ii) the fact that most of the processes modelled in the study have not been adapted to each region and may not properly model regional realities not accounted for in the ecoinvent® database, which has been primarily developed to model European processes; (iii) the high uncertainties involved due to the several tools used, the mapping of databases with GTAP considered, the lack of regional data. The mechanism of the relationships between crop consumption and land use changes is effectively described in [20,21], where the standard version GTAP is modified and used to predict global changes in supply and use of arable land caused by increased wheat demand in Brazil, China, Denmark and the USA. In the standard GTAP the availability (supply) of land is constant. This means that shocking the demand for a specific group of crops will only result in displacement and intensification. Following the approach proposed in [50], Kløverpris et al. [21] apply the integration of the so-called land supply curves in GTAP, which

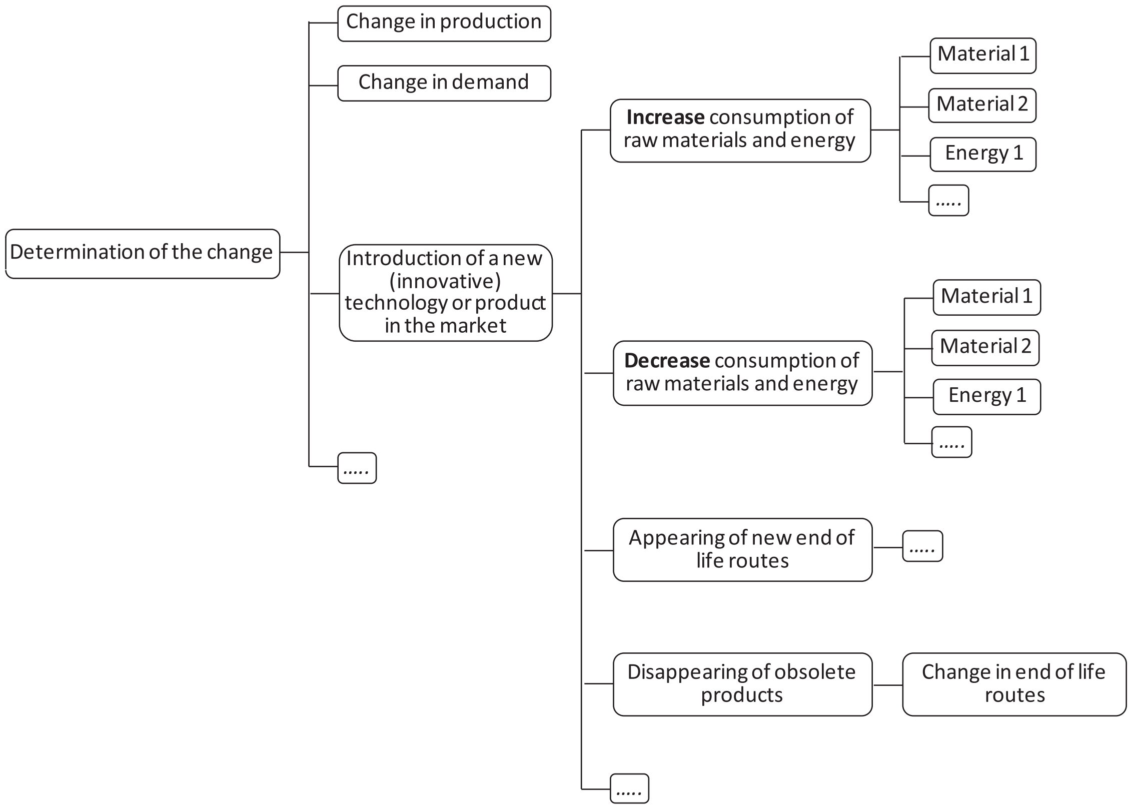

Fig. 3. Collapsed MindMap tree illustrating the simplified methodology of C-LCA, mainly based on D18 of the CALCAS project [31].

allow the use of agricultural land to be determined by the model. Furthermore, elasticities are adjusted to reflect long-term changes. A further critical element of GTAP, modelling the effect of crop demand on technological development and hence intensification, is instead ignored in the core scenarios assessed in [21] and is only investigated in the sensitivity analyses. An extension to the GTAP database is performed in [51], where the standard GTAP database is enhanced (including, amongst other things, ethanol from food grains, ethanol from sugarcane, and biodiesel from oilseeds) to properly trace the link among the biofuel, vegetable oil, food, feed, and livestock industries.

As remarked by Kretschmer and Peterson [52], modelling bioenergy poses the challenge that, on the one side bioenergy is not a production sector that is included in the base year SAMs[9] of CGE models, so that it cannot be calibrated in the usual way; on the other side, it is not a pure future technology but one has to account for the production and trade patterns that exist today as a result of governmental support.

2. Materials and methods

The C-LCI modelling approaches presented above are now structured against a number of criteria which cover most of the important operational aspects of the C-LCA perspective, with the aim of highlighting the opportunities and bottlenecks associated to their practical implementation.

[9] A SAM is a matrix which accounts for the incomes and expenditures of all agents in the economy. The agents comprise producers, consumers or households, government, export and import sectors, investments and savings. The columns in the SAM represent the expenditure on the use of a particular commodity, like payments to labour by the iron and steel industry or the use of natural gas in power generation. The rows show the sources of income for a particular commodity.

2.1. Setting up the market boundaries

The way the market is delimited in the simplified approach [31] is depicted in Fig. 3, and further developed in the SI. The starting point of the market delimitation is the determination of the type of change one is assessing: is it a change in production, a change in demand, or the addition to the market of a new technology or product? Then three main dimensions are analysed:

- *Geographical dimension*: Where does the change take place? Is there a net consumption (i.e. imports exceed exports)?
- *Temporal dimension*: Does the market change during time (peak hours, rush hours in telecommunications, tourism, seasonal differences between summer and winter, etc.)?
- *Market segment*: What is the functionality related to the main function of the project, its price, its technical quality, its specific environmental properties, etc. Is it a niche? As default, if no information is available to justify a market boundary, it is advisable to assume that no market boundary exists, since this is the most general situation [31].

PEMs treat international markets for a selected set of traded goods, in the specific case agricultural goods. The market delimitation is therefore implicitly defined by the model structure. PEMs consider the agricultural system as a closed system without linkages with the rest of the economy (non-agricultural sectors, other regions or countries) and allow for a detailed representation of agricultural and bioenergy production and land use restrictions. Effects of the rest of the domestic and world economy on the agricultural system may be included in a top-down fashion by altering parameters and exogenous variables but this is still a workaround solution.

CGE models compute the change in welfare subject to clearance of all markets (i.e. supply equals demand in all markets).

Therefore, in principle, the market delimitation can be rather broad, and broader than in the previous approaches. However, as per Walra's law [53], if n−1 markets clear, then the n-th market also clears. Hence we fall short of one equation, which is then made up by another equation called the numeraire. All prices in CGE models are relative to the numeraire. The availability of the input–output data largely determines the details that one can study using a CGE model, and therefore the market delimitation as well. The problem gets worsened in multi-country trade models, as some countries may not have data for all sectors and commodities available for the other countries. In such a situation, one is forced to aggregate all countries to a common data of sectors and commodities for consistent trade flows. As a result, in practice, the ability of CGE models to consider large market boundaries is hampered by the lack of pertinent and reliable information and data.

2.2. Defining the scale

The definition of the scale of the change to be studied in C-LCA is influenced by the market delimitation. If the change introduced has a limited dimension (i.e. it is compliant with the ceteris paribus assumption), such that it does not modify the trend of the market, then it will be defined as a "marginal" change, classified as "Situation A" in the ILCD handbook [28]. For example, considering that bio-plastics are receiving much attention in the emerging topic of green chemistry (since they can be made from renewable resources or will degrade easily later in nature or under industrial conditions), it is likely that in the near future more and more land will be needed to produce biomass for the production of bio-polymers. Now, let us suppose a plastic producer which holds a small share (say less than 5%) of the world plastic market decides to convert its production entirely towards bio-plastics. In this case the plastics market will keep having the same trend, i.e. will not be affected by this particular decision. But if a new directive came in force in Europe, banning all the fossil polymers and imposing their substitution with bio-polymers, then the change would be large and the traditional plastics market would certainly be affected by this change, thus its trend would certainly slump (i.e. the change cannot be considered as marginal). This would be a typical situation implying large changes in the background system of an LCA study and thus classified as "Situation B" in the ILCD Handbook. In the simplified approach, the scale of the change is therefore defined by the decision context and leads to classify the study in one specific situation (A or B).

In PEM, the level of shock depends only on the feasibility of the problem and this depends on the constraints. If the change that is envisaged renders the problem infeasible, then it is up to the modeller to identify the binding constraints and possibly relax them if the system permits. To cite an example, producing biomass for biofuels using the existing land under cultivation would lead to change in cropping patterns and possibly a polarisation of crop output. However, the constraint of not permitting forest land to be changed for cultivation could be the binding constraint and if a large shock implies that the amount of biomass needed cannot be supplied by the existing cultivable area, the forests might have to be cut down. Else the demand would have to be scaled down. As a result, the translation of the scale of the change, which is defined by the decision context, into the PEM cannot be trivial and involves additional work on model constrains.

In CGE modelling, the level of shock is sustainable if the problem is feasible. Most CGE models have a CRS technology and with this assumption the producer can produce as much as possible. The constraint on the system is imposed by the factor availability. Excess demand arising from a shock would translate unequivocally into price rise. The prices and quantities are determined endogenously and in sectors where quantities are fixed, prices adjust to clear the markets. As a result, the defined scale of the change can be easily supplied as input to the CGE model under the condition that it is realistic.

2.3. Relevance of the time horizon

The time horizon of the change assessed in the study varies significantly depending upon the sector of application. In the agriculture sector, a one-year horizon could be considered a short-term one, whereas a two-year horizon could be considered as a long-term perspective. This is related to the intrinsic nature of agricultural processes, where the yield is harvested year by year. In the energy sector, on the other hand, a two-year horizon would be still a short-term one, since several years are needed to plan a new energy investment strategy and build a new power plant. Mattsson et al. [54] show that even a change in the annual electricity demand by 1 TWh can still be regarded as small, since it affects the same technologies as a change of 1 kWh, which means that the effects are linearly related to the size of the change. Finally, if the change introduced implies that even a change of technology is needed to meet the demand, then the change should be considered as a very-long-term one. In the simplified approach, the time horizon is therefore set by considering the specificities of the market sector and by applying simple rules of thumb.

PEMs go beyond the simplified approach in the incorporation of the time dimension, by possibly including dynamic modelling of specific features, depending on the nature of the decision context. Dynamic modelling has the added benefit of time progression, but whether this added dimension would lead to additional insight in C-LCA remains to be demonstrated. To cite an example, the farm problem is a static and a dynamic one. It is static in that crops are grown once or twice a year, and depending on the "global" output, the prices are determined in the market. To hedge risks, the farmers can sell their crop in the future markets but that means also a cap on the potential upside on price due to scarcity of output. There are no control variables at the disposal of the farmer that would affect the future productivity of the crops. This renders the problem static for solution for each year. For agriculture operations with animals, the problem is dynamic as livestock operations are mostly cyclic and may extend even close to a decade. The control variable available to the farmer is the number of animals to be slaughtered which would have an impact on the herd size in the future, which means changing feed, and output prices for meat and milk and other animal products. Thus the problem is dynamic in nature and amenable to dynamic programming. The temporal dimension can therefore be easily integrated into PEMs when the relative information is accessible. It is important to note that both short and long-term perspective (transient periods) can be simulated with PEMs.

Similar conclusions are drawn for CGE models, which are either *sequentially dynamic* or *fully dynamic*. In sequentially dynamic models, the CGE model is solved for each time period and the factor endowments like labour and capital are augmented year by year. The labour and capital can grow according to the growth rate, which depends on the savings. Whether savings determine investments or investments determine savings is a choice the modeller has to make. Capital grows according to the following equation:

$$K(t+1) = (1-\delta)K(t) + I(t) \tag{4}$$

where $I(t)$ is the investment at time t and δ is the depreciation rate of capital. Like for the case of PEMs, both short and long-term perspective (transient periods) can be simulated with CGE models.

2.4. Introducing constraints

If the dimension of the demand is not marginal, then the market needs to react in the short term and the prices will

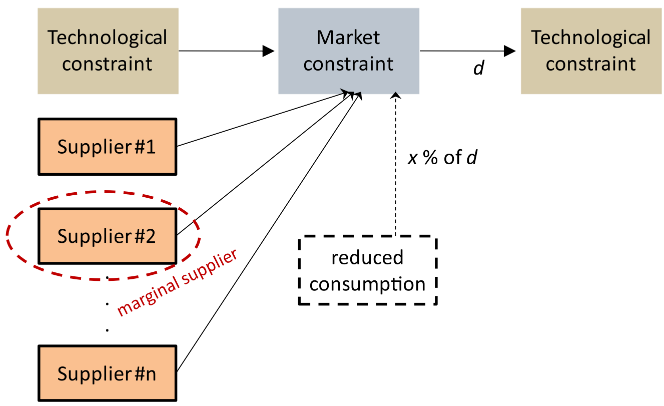

Fig. 4. Representation of the short-term effect induced in a constrained market by an additional demand of a commodity.

probably rise. If the market is constrained (i.e. not fully elastic), as it is generally the case, C-LCI heeds the existing constrains in the modelling. Let us consider an additional demand *d* of a commodity, stemming from the increased need of a raw material by an "average buyer"(Fig. 4). This will translate itself not in a direct supply of the same amount *d* of the commodity by a unique "average producer", but in a possible supply by multiple producers (in different shares) or still in a supply by a unique supplier that however now responds to the increased demand as the market's *marginal supplier* determined by a market equilibrium. Since in this new framework the market is not perfectly elastic but can also be constrained, it is possible that, due to the existing constraints (whatever their origin), the increased demand *d* cannot be met totally through new production, but a certain amount of it (say *x*% of *d*) has to be provided in terms of reduction of its consumption by a different buyer. The latter, for instance, could be no longer able to afford its previous consumption of the commodity at stake, due to an increase of its price (that the new buyer requiring an additional amount *d* is instead willing to pay). This situation is defined as a *market constraint* [55].

Another type of constraint arises in the case in which the product at hand is a secondary product of a production process. It could be the case that the producer of this commodity, even if technically able to meet an increased demand, will not find economically effective increasing the production of the main product (determining product) just to give rise to an increased production of the secondary product, simply because in this way there would be a surplus of the determining product that the market would not be able to absorb. Let us take the example of biomass fly ashes. They may be used directly as a fertilizer or as soil improver or may be used as a raw material in the production of mineral fertilizer, or even as building material or component in the production of building products, for example as filler in cement blends or in mortars for special applications. In this last case a potential application has been found as filler in C-FIX, a concrete-like material [56]. If the production of C-FIX increased abruptly and significantly, it would be difficult to satisfy it using fly ashes coming from the energy industry, and on the other hand the energy producers would not burn more biomass and produce more energy just for meeting the increased demand of C-FIX. This situation is defined as *by-product constraint* [55].

Two other possible kinds of constraints can be taken into account. One is the *technological constraint*: only suppliers with a specified technology level will be included in the pool of the possible suppliers. As an example, if there is an additional demand for hydropower production in a regional context where the hydropower production potential is already exploited at its full capacity, this increased demand cannot be satisfied because of this technical limitation. The other is the *regulatory constraint*: product (e.g. milk) quotas or emission quotas; trading taxes, subsidies, etc.

The simplified approach only takes by-products constraints into account, i.e. apart from by-products it assumes a fully elastic market adopting a long-term perspective, when no activity will be constrained. The model described as "Situation A" ("Micro-level decision support") in the ILCD Handbook [28] follows this type of reasoning as well.

PEMs largely deal with a single criterion optimisation. The objective function can be minimising costs, losses, variance or maximising profits, gains, returns subject to constraints that may range from operational, to behavioural to capacity. If there are multiple products from a production process, the output of these products are pre-defined technical coefficients and the output of the process will be determined by the constraints that are binding for the process and can be adjusted at different levels of granularity. The model is normally subjected to sensitivity analyses to gauge the impact of these parameters on the objective function. The way constrains affect the final consequential results is therefore quite different for the simplified approach and the PEMs approach. Whereas the first defines the constrains and their effects using the market information available, the latter incorporates the mechanisms related to constrains and performs a single criterion optimisation based on these (endogenously defined) constrains.

Contrary to the previous approaches, CGE models do not have any constraints per se. A set of *n* simultaneous, non-linear equations have to be solved. The only constraints the system is subjected to are the limitations on factor supplies. This is true even for complicated energy models, wherein liquid fuels to run automobiles are obtained from processes like liquefaction of coal. Given the vast deposits of coal, it is unlikely that they will be exhausted in one fiscal year, or that the machines that are needed to excavate coal are limited. Eventually the constraint would be constituted by the labour that will operate the machines used to extract the coal, which will determine the amount of liquid fuel obtained from coal liquefaction. As a result, the role of a constraint is played here by the fundamental principle behind CGE models, i.e. market clearance. The consequential effects are not the result of constrains but of the necessity to clear the market, which modify the expenditures in the economic sectors.

2.5. Dealing with multi-output processes

The crucial distinction made in the simplified approach is between combined and joint production. In *combined production* the co-products are deliberately coupled and their output volumes can be independently varied (e.g. transportation of passengers and cargo by an airplane), while in *joint production* the co-products are causally coupled and their relative output volumes are fixed (e.g. production of chlorine and caustic soda, whose reciprocal mass ratio is univocally determined by the stoichiometry of the chemical reaction). In the case of joint production a change in demand for one of the co-products may or may not lead to an increase in the production volume of the co-producing process. Such a change will occur if the co-product at stake is a *determining co-product*, i.e. if a change in its demand will affect the production volume of the co-producing unit process [31].

PEMs deal explicitly with joint products as the output of joint products determines the profitability of the system under investigation. Thus, for example, harvesting each crop leads to a certain percentage of straw and plantation of a specific crop on a specific soil type has an impact on the soil characteristics in the future. The environmentally harmful by-products would also be modelled and, if needed, specific constraints could be added to limit the production of these toxic by-products. For example, the amount of carbon dioxide from coal, natural gas, hydro and nuclear power

plants would be a legitimate by-product (albeit zero for some processes). The political need to cap CO_2 emissions would imply that some processes would then run below capacity and would trigger more expensive cleaner processes.

Normally industries or sectors produce multiple commodities. In CGE models one assumes that these multiple commodities are produced in fixed proportions based on a transformation matrix that transforms output of a particular sector into multiple commodities. CGE models also use two additional assumptions when it comes to transformation of inputs to outputs via a production process. The commodity technology assumption assumes that each commodity uses the same inputs irrespective of the provenance of the inputs. For example, electricity is produced in the electricity sector using a turbine, while other sectors might also produce electricity as a by-product, using diesel generators. The commodity technology assumption assumes that the electricity produced in the other sectors also use turbines to produce electricity. The industry technology assumption assumes that each by-product is produced using the same inputs as the main technology, thus electricity produced in the textile sector will use the same inputs as those used to make textiles and not those used to produce electricity by turbines. Then the principle of market clearance applies as usual and secondary outputs contribute to the calculation of the consequences of the change.

2.6. Assessing direct and indirect land use changes

In the simplified approach developed by Schmidt [24] land use change is determined by identifying (based on expert's judgments) the long-term marginal supplier of a specific crop and following the replacement/displacement chain to identify the marginal crops and the amount of them replaced by the new crop (based on the ratio between their respective yields) both in the studied region and in the marginal supplier region(s). The amount of land affected by the use change is then determined as a function of the determined amount of the various crops and their respective yields. The expert judgments should be normally based on some physical properties of the substituted products, such as protein content in cereals, or fatty acid composition in oils.

Despite PEMs often include land use modelling (contrary to CGE models), many of them use reduced-form supply equations, or have yield and area response equations without an explicit land market. Thus constraints on land aggregation are lacking and competition between alternative uses is weak, implicitly captured only in the cross-price elasticity of the area response equations or even non-existent. Since the competition for land with other uses is at the heart of biofuel analysis, this is a significant limitation of PEMs [52]. Modelling LUC requires a detailed agricultural model (as agriculture output cannot adjust instantaneously), which is difficult to incorporate into traditional CGE models. The decision by farmers to plant a specific crop depends on the expected market prices of various crops. Also detailed information on fertilizer use, response of crops to fertilizer and availability of water (natural or artificial), prices of livestock, milk and subsidies play a major role.

An important point of discussion concerns the step from the aggregate scale of the results of economic equilibrium models and the higher resolution spatial scale needed for environmental assessment. Several research projects have proposed methods linking economic models and their results for larger administrative units to geographic approaches dealing with land use at less aggregated spatial scales. At the European scale, examples are provided by SENSOR [57], EURURALIS [58], INSEA [59], GENEDEC [60], CAPRI-Spat [61] and CAPRI-Spat and CLUE combined [62], LUMOCAP [63] or, at the global scale GLOBIOM [64]. All these approaches deal with the same issue of relating coarse scale economic information to geographic information about land use. They have implemented different methods to link these domains. Some approaches apply down-scaling methods in which economic simulation results are spatially disaggregated based on geographic information. Other approaches account, to some extent, for feedbacks between the economy and land allocation. Hellmann and Verburg [65] applied a spatially explicit model for the spatial allocation of biofuels industry, presenting a case study about Germany. The paper provides a methodological framework which makes it possible exploring the impact of policies on the development and location of the biofuel industry. In van Meijl et al. [50] the authors developed an extended version of the GTAP model, which combines the advantages of the global CGE modelling approach, taking into consideration the impact of non-agricultural sectors on agriculture and a full treatment of factor markets with the specific features of PEMs concerning land modelling. Moreover, the macro-economic model is linked to the bio-physical-based modelling framework IMAGE. Macro-economic drivers like population and economic growth (see [66]) are used as input in both the GTAP and IMAGE model. The economic consequences for the agricultural system are calculated by GTAP. The output of GTAP is, among others, sectorial production growth rates, land use, and a yield factor describing the change in land productivity because of technology improvements and the degree of land intensification. This output is used by IMAGE to calculate yields, the demand for land, feed efficiency rates and environmental indicators. This procedure delivers adjustments to the achieved changes in yields and changes in feed conversion, which are fed back to GTAP.

2.7. Quantification of the change

Once completed the above described steps, the pivotal point to address is the quantification of the change.

In the simplified approach this implies two further discriminative elements (refer to the MindMap tree in the SI). The first element is the analysis of the trend volume in the affected market, which is quite independent from the outcomes of the previous steps. The assumption of a steady or constantly increasing market is quite appropriate for many reasons, e.g. increase of the world population and nature of modern economy based on a constant increase of consumption. The second element is the determination of the change in supply and demand, which is indeed highly dependent on the previous steps and especially on the market delimitation and the scale of the change. This change leads to different consequences according to the nature of the market ("unconstrained market", "constrained market", "very constrained market"). The unconstrained market represents a case of perfect elasticity. In this kind of situation a part of the suppliers can be constrained, but the demand will shift on the unconstrained part of the market. Among the unconstrained suppliers/technologies, the most competitive in the long-term perspective should meet the demand. This will likely be the best technology. If all the suppliers in a specific market segment are constrained, or if one or more production factors are not fully elastic, the long-term demand elasticity of the marginal consumers must be estimated and the consequent change followed downstream in the life-cycle. Identifiable long-term constraints that are regarded as questionable should be analysed in separate scenarios. Once determined which product can/should meet our demand, the study can move to the third step under the parent node "Change in demand", that is "Consequences of the change" (see SI). In the assumption of dealing with a marginal shock (i.e. additional biogas production), the additional demand can be met directly through an increased production of biogas from fermentation of energy crops (no additional constraints need to be taken into account). Thus the

tree forwards the practitioner to the upper level node "Change in production". As the conditions of the study for biogas have been previously determined, one can directly proceed to the consequential assessment of materials and energy involved in the production of biogas. Let us assume that all changes in materials and energy consumption are marginal, on a long scale and coming from a process producing a single product (no co-production). It means that markets are perfect and unconstrained and that the relation between change and supply is linear with full elasticity. However, for crops it is not perfectly reasonable to assume no reaction of the market since prices of all types of crops are indirectly interrelated in a worldwide market. Additionally, the price of production of a same crop can vary according to the regulations in force (determining for instance constraints on the land use and utilisation of fertilizer), the land yield (quality of soil, climatic conditions), the distance between the crop producer and the purchaser and so forth.

A PEM represents an alternative approach to the described decision tree. After the model in the base case has been calibrated (to replicate the base year data and behaviour), the model is shocked based on the new decisions made or taken. For example, in a diet problem, one has the information on the calorie, protein, fat, carbohydrate content of peanut butter, but if one discovers that it leads to an allergy, then that the amount of consumption has to be restricted. This implies the constraint on peanut butter consumption has to be modified and the model solved again for another optimal solution. The difference between the original and the new equilibrium will be the quantification of change. There is a distinct possibility that the problem may not be feasible and in such a case, the constraints have to be relaxed to find a solution.

In the case of CGE models, based on the policy to be assessed the modeller can give a shock to any of the parameters and the model will compute the changes in output and prices that are commensurate with the market clearing in all sectors. In case the constraints are binding such that there is no feasible solution then there is no quantification of change.

3. Discussion

The critical review of the modelling approaches pointed out two key differences which could elucidate their possible integration in a common framework.

First, the modelling approaches radically differ as per the computational and conceptual structure beneath. Whereas the simplified approach follows a sort of decision tree aiming at identifying and quantifying the chain of consequences one after another, using simple rules of thumb, PEMs and CGE models consist in finding the solution of an allocation problem. In the case of PEMs, the allocation problem consists in the optimal (meaning maximising the revenue) distribution of resources and production functions. In the case of CGE models, the problem is the allocation of money flows (reflecting production functions and other econometrics) between economic segments in order to reach the market clearance at different time steps. These conceptual differences are indeed fully complementary and reflect different stakeholder's and decision maker's perspectives, which have to be clearly stated and discussed when presenting the decision context of the LCA study. They are all legitimate but respond to different questions and decision making processes.

Secondly, the approaches adopt complementary time horizons of investigation as well. As also argued by Gallagher [67], CGE models are representing what is likely to happen in the medium term when markets can adjust, while PEMs give a better picture of what happens in the short term and in circumstances when adjustment is difficult. In relation to C-LCI, these two different modelling perspectives correspond to two different consequential perspectives. Although in principle LCA focuses on the long-term, both in LCI and LCIA steps (this is well reflected in the simplified C-LCI illustrated), one could argue that using PEMs the consequential effects in the short term are evaluated, whereas with CGE models the medium term is focused. This is indeed another interesting complementarity between the modelling approaches, which could therefore contribute together at responding to a decision context ranging from the short to the medium-long term.

An additional possibility to combine the advantages of PEMs and GEMs is, in principle, linking both types of models and there are indeed some approaches in this direction [68]. In [69] this approach is also used to analyse bioenergy policies. In [70], CAPRI[10] is used in conjunction with the GTAP model, to estimate both the global impacts of EU biofuels policies and the detailed, regional changes in land use and nutrient surplus. CAPRI and GTAP have a global coverage with a different level of country detail (CAPRI has around 53 countries/regions, GTAP Version 7 has 113). The major complementarity between the two models is in their different sector detail. CAPRI has an advantage over GTAP in its detailed modelling of agriculture, both in terms of product details and in modelling the different elements of the CAP. GTAP has less detail in agriculture but covers the whole economy, i.e. incorporates general equilibrium feedbacks between all sectors of the economy. Since they are different types of model (partial equilibrium versus general equilibrium) the results will never coincide perfectly, even if scenario assumptions, data, and structural parameters were made consistent as far as possible. A parallel application of both models would, for example, produce two sets of results on changes of agricultural output values in the EU. By linking the CAPRI and GTAP models, it is possible to obtain an improved analysis of the impact of EU biofuels mandates (both on international markets and land use) as well as on EU environmental outcomes. In [70], the authors couple the two models by modifying the GTAP model in order to include a summary of the regional supply models of CAPRI, which is then applied to capture global land use effects and the interplay of agricultural and energy markets and biofuel policies. By taking the resulting equilibrium price changes and applying them to the supply models of CAPRI it is possible to elicit highly disaggregated changes in farming practice and their impacts within EU. These regional results can then additionally be spatially disaggregated to a $1\ \mathrm{km} \times 1\ \mathrm{km}$ resolution (see [62]) to provide input to bio-physical modelling at an appropriate scale [61], or fed into a LCA of energy use of EU agriculture [71]. On the other hand, global impacts of EU policies such as on poverty in developing countries [72] can be analysed with post-simulation analysis of GTAP results. In addition to global LUC and the associated GHG emissions, GTAP generates equilibrium price and quantity changes for all commodities, globally, including EU crops. The crop price changes are then fed back into the CAPRI model in order to elicit detailed EU impacts on land use and the environment. However, Britz and Hertel [70] showed that when the EU agricultural sector model CAPRI is used as the supply side in GTAP there is much greater land use in the rest of the world as a reaction to EU biofuel mandates and less in the EU which results in large differences for GHG emissions. When looking in detail at the results from this case study and the others applying the different modelling approaches analysed in this paper, it is indeed difficult to compare, not only because different policy scenarios are analysed, but also because output variables, geographic areas and driving forces are different [73]. While there are large differences even between models of the same type, based on the same basic data, there is some evidence that CGE models lead

[10] http://www.capri-model.org

to smaller increases of agricultural prices than PEMs, i.e. to potentially less relevant changes in C-LCI. This is probably mostly due to the very large implicit supply elasticities in the CGE models [52]. Supply-side response is therefore of crucial importance.

As it is apparent from the critical review, the implementation and eventually combination of economic modelling approaches to C-LCA raises two major challenges: (1) the efficient information and data flow from the economic equilibrium model to the C-LCA model (their implementation shall be practical enough to directly include economic modelling information into LCI database); (2) the data collection and scenario development to feed economic models, both from literature studies and stakeholder's interviews. As a result, a perfectly integrated framework of the three approaches presented all over the paper seems to be neither feasible, nor entirely realistic. The simplified approach is quite useful as a preventive screening of the scale and the nature of the consequences implied by the decision context being assessed. Once the decision context (large-scale/small-scale; micro-level decision support/meso-level decision support/macro-level decision support) has been clearly identified, an appropriate model can be chosen. Given the complexity and the scarce level of customised control on variables the user has with comprehensive CGE models like GTAP, for many C-LCA case studies the best approach would probably consist in the development of a dedicated PEM, followed by a fine-tuning step based on the accounting of foreign trades with selected regions treated with a great amount of detail, while the description of other regions is confined to a smaller range of variables. If the aims of the study require it, downscaling methods could be possibly pursued in order to spatially disaggregate economic simulation results.

An example of an integrated framework where economic models and LCA are combined was successfully achieved in the project LUCAS (indirect **l**and **u**se change effects in **c**onsequential life-cycle **as**sessment of bioenergy), for the assessment of ILUC effects into C-LCA of biogas production from maize in Luxembourg at the horizon 2020. A PEM was specifically developed for the Grand Duchy of Luxembourg, following the farmer's revenue maximisation principle, and then applied to derive the C-LCI of biogas production. A short description of the model and the results of the project is provided in [74]. Hereinafter, the integrative modelling approach pursued in the project is described, following the line of reasoning critically discussed in this paper. The combination of PEM and C-LCA is achieved as a soft-link [75], i.e. the results from the PEM are manually fed into the C-LCA model built in the software Simapro®. For the PEM development, detailed information was available on the cropping patterns by size of farms but the integrated nature of agriculture in Luxembourg (all the farms in the country practice both husbandry and farming) and lack of detailed information on animals by farm implied that the analysis was restricted to the aggregated national level. The total gains in the system from crops and animals were maximised by the model. The constraints on the system were the maximum permissible limits to change in crop area allocation, the response of yield to fertilizer inputs, the metabolic requirements for animals for each type of feed. Since the model focused on the farm returns in a particular year, decisions of breeding and culling of animals for meat were exogenous. Different scenarios for 2020 were defined based on the current situation of the agricultural system in Luxembourg (at reference year 2009). These scenarios were modelled based on a set of assumptions considering changes in the agricultural policy (computing land use changes in 2020 including and excluding animal costs; allowing and forbidding meadows and pastures conversion into cropland; allowing and excluding rapeseed substitution, etc.). Moreover, the modelling for each scenario included a "shock" approach, in which an additional input of maize was considered, and a "non-shock" perspective, in which the additional inputs for biogas production were disregarded, i.e. the agricultural system was optimised without no constrain on biogas production. The "shock" triggering the model was estimated to 80,000 t of additional maize dry matter to be produced, taking into account the target set for 2020 by the Luxemburgish Renewable Energy Action Plan [76] in terms of energy production from biogas (144 GWh).

Starting from this additional demand, the PEM was solved using GAMS [77] to calculate the necessary changes in the agricultural system to meet the demand[11] maximising farmer's revenue. The PEM provided two main results: (1) the change of crop production patterns, i.e. the primary consequences on Luxembourg's agriculture system of the planned production of maize (forage crops are included, making the link to the consequences on meat and milk production); (2) the changes of land use type (starting from which it was then possible to calculate the related primary consequences in terms of modified emissions (e.g. CO_2) and land transformation impacts). The land transformation impacts were estimated using two different approaches: (1) the traditional approach firstly defined by the SETAC Working Group on LCIA [78] and subsequently improved by Milà i Canals et al. [2], based on the quantification of physical occupation and/or transformation of land quality; (2) the approach operationalized in the LANCA model [79], based on the concept of land functions and the calculation of different land use indicators (erosion resistance, physicochemical filtration, mechanical filtration, biotic production and groundwater replenishment). Based on the results obtained, the C-LCI for the agricultural system in Luxembourg was modelled. Data for this inventory were obtained from major datasets at a national and international level (FAOSTAT,[12] EUROSTAT,[13] STATEC[14] or KTBL[15]) and the background data were retrieved from the ecoinvent® database [80]. This phase was followed by LCIA to obtain a comprehensive view of potential environmental impacts and damages, carried out using Impact 2002+ [81]; ReCiPe [82] and USEtox [83]. A schematic representation of the integrative modelling approach adopted is presented in Fig. 5.

The approach adopted allowed the representation of a more realistic behaviour of the market, overcoming the underlying concept of an "average producer" and "average buyer", introducing the previously determined market's *marginal supplier* determined by the PEM and using the ecoinvent® database consistently with this new piece of information. For the scenarios in which the increase in maize production is not foreseen, the environmental burdens linked to land use changes were shown to be limited. No need for intensification of the existing and new areas to meet demand for maize has been observed.

To study the impacts of increased agriculture prices, the modelled changes were then propagated outside the national boundaries, using GTAP, to account for possible additional environmental impacts. Agriculture turned out to have a very small share in the value added in the economy and increased demand for maize which may displace existing crops did not show serious economic impacts. In this specific case the development of an ad-hoc PEM seems therefore to be the most appropriate modelling approach.

4. Conclusions

The paper provides a critical review of three possible modelling approaches for C-LCI, with specific focus on the bioenergy sector

[11] Respecting the constraints imposed to the model, such as the maximum permissible limits to change in crop area allocation, the response of yield to fertilizer inputs, the metabolic requirements for animals for each type of feed.

[12] http://faostat.fao.org/

[13] http://epp.eurostat.ec.europa.eu/portal/page/portal/eurostat/home/

[14] http://www.statistiques.public.lu

[15] http://www.ktbl.de/

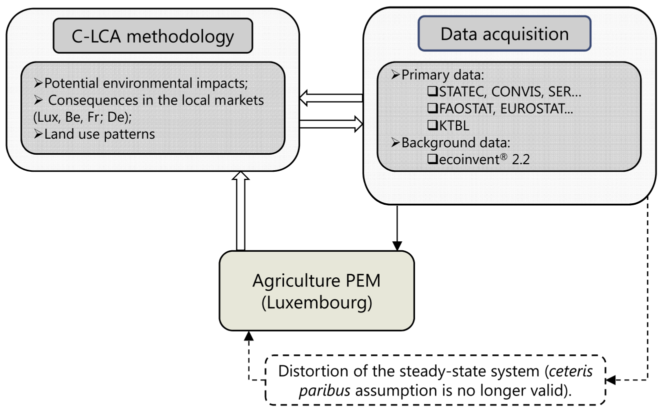

Fig. 5. Schematic representation of the model implemented in the project LUCAS (the distortion of the steady-state situation is represented by the additional demand of 80,000 tons of maize).

and the evaluation of the related LUC and ILUC effects. As the paper pointed out, the (to-date) most comprehensive approach to model (I)LUC is rooted on economic modelling of global (cross-sectorial) market equilibriums, in order to determine the marginal activities (and the consequent new land use patterns) affected by a specific additional demand of energy crop imposed in a specific location. However, this kind of modelling would generally entail heavy resources and time investments. As the paper shows, a simplified approach, based on rules of thumb, may be applied beforehand as a preventive screening of the scale and the nature of the consequences involved by the decision context at stake. The results from the simplified approach will influence the choice of the economic approach to adopt, ranging from PEM and CGE modelling at different levels of details. The latter are defined first by the decision context of the LCA and then by the level of granularity required for the results, the abundance or scarcity of the market and inventory information available for modelling, the human and economic resource one can invest in the development of a model, among other criteria. Hybrid solutions consisting in a combination of PEM and CGE models are possible, as in the mentioned application case for the C-LCA of biogas production in Luxembourg. The combination is particularly relevant to consider different time horizons (short and long-term perspective), different scopes and level of granularity of the markets (e.g. from a very specific analysis of regional market sector to a multi-sector world analysis), spatial specificities (especially related to land use changes) as well as the full range of constrains (technical, regulatory, market, etc.) which motivate a C-LCA approach. It shall however be noted that data availability strongly limit the effective development of combined PEM and CGE solutions, as pointed out in the critical analysis for most of the criteria. All these elements are defined on a case-by-case basis by the decision context targeted by the C-LCA study. The consideration of several farming types to specify parameters affecting the evolution of crop production patters, and also their mutual relationships, requires important efforts for inclusion in the modelling, because of the difficulty to translate these variables into costs. The modelling of the influences of crop production patters on the food sectors is not trivial because of the difficulty of assigning a clear and robust aggregated market relation between forage crops and meat and milk.

Beyond technical limitations, equilibrium models obviously have some other limitations. For instance they generally fall short in considering non-economic constraints such as behaviours related to habits, cultural heritages or additional regulatory constraints, like for instance the fear of generating production surplus that the market would not be able to absorb. Behaviour has to do with autonomous changes in time and exogenous changes. The use of more behaviour-oriented approaches, like agent-based modelling [84], could be a meaningful approach for proper consideration of these elements in C-LCA. Similarly, other research issues, linked to the modelling approaches discussed in this paper, which deserve to be properly addressed by further research are data gaps and uncertainty and the inclusion of larger scale effects (side effects, rebound effects, etc.).

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Appendix A. Supplementary information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.rser.2013.04.031.

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